NASA Contractor Report 3093

Present Status of GaAs

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PART A

LITERATURE SURVEY

An extensive literature survey on GaAs (research, development and applications) was carried out to establish an up-to-date reference source. We utilized a computer reference bank based primarily on the coverage of the Chemical Abstracts. The period included, thus far, is December 31, 1970, to December 31, 1977.

We considered it important to carry out an analysis of the literature survey to identify the leading institutions involved in GaAs research and applications, to assess the trends and present status of research and development in GaAs crystal growth and to evaluate the evolution and present status of GaAs applications with the expectation that future trends might become apparent.

We realize that the present analysis has limitations; the most important one relates to the fact that a good fraction of applied research and development is not published in the open literature. However, we believe that this limitation does not impair significantly the validity of the conclusions regarding general trends and interests, particularly since this analysis was complemented by discussions with top experts in the field and by the insight gained in the recently held Workshop on GaAs.

The numbers of publications on GaAs which were recorded from 1971 to 1977 are shown in Table I. The steady annual increase in the number of publications over the past seven years certainly reflects the steadily increasing interest in GaAs basic research and applications. Between 1971 and 1977 the number of publications per year in English increased by a factor of 1.8, and there is no evidence that this trend is leveling off.

The following analysis of the literature survey is based on publications in English or translated into English; patents are not included. In 1977 these publications represented about 70% of all publications recorded in that year (excluding patents).

Leading Organizations Involved in GaAs Research and Development

During the period 1971-1977 the United States contributed 48.5% of the publications in English and about 30% of the total number of publications. Other contributing countries, in the order of number of publications, are Japan, Great Britain, West Germany, USSR* and France. Table II lists organizations which have contributed more than about 1% of the publications on GaAs. It is seen that BTL has contributed remarkably to the world's GaAs research and development open literature.

On the basis of the publications originating in the United States we have identified the organizations which have contributed most to the GaAs open literature. The leading twenty organizations, their geographic locations and their contribution (in percent) to the total publications from the United States are indicated in Fig. 1. Here again, it must be noted that BTL has contributed about 20% of all publications from this country.

Crystal Growth

The number of publications devoted per year on various methods of crystal growth in the period 1971-1976 is shown in Fig. 2. It is interesting to note that the total number of publications in 1976 increased by a factor of 7.5 since 1971. It is equally interesting to observe that this striking increase represents almost entirely an increase of publications on epitaxial methods of growth and particularly on LPE.

*Considering that many USSR publications are not recorded in the Chemical Abstracts, that a significant fraction of the publications in English and in "other languages" originated in the USSR, the number of publications on GaAs from the USSR probably exceeds that from the United States.

The strikingly increasing interest in LPE is certainly consistent with the fact that GaAs device technology is based on epitaxial layers. It is surprising, however, to observe the lack of research involvement in growth from the melt, in view of the fact that all bulk GaAs single crystals used for substrate material in epitaxial growth are grown from the melt.

One might conclude from these results that either growth from the melt presents no serious difficulties or that the quality of the substrate material is of no consequence in device fabrication and device performance. One might also conclude that research and development results on melt-growth are not published in the open literature. As pointed out below, none of these conclusions is valid.

Growth from the melt and the role of the quality of the substrate in GaAs device technology were extensively discussed in the recently held Workshop on GaAs (attended by experts from many organizations indicated in Fig. 1). It was generally agreed that the quality of bulk GaAs single crystals is, by and large, very poor. It was also agreed that the substrate is by no means a passive component in GaAs devices and that, in fact, poor quality is responsible for the very low yield and erratic performance of GaAs devices. It was finally acknowledged that essentially no basic research is in progress in this country on GaAs growth from the melt and that the major suppliers of GaAs crystals are two or three relatively small organizations carrying no fundamental research programs. The present incongruous status of bulk GaAs growth was attributed to the lack of economic motives within the private sector for financing needed research and development.

GaAs Applications

On the basis of the present analysis the number of publications per year on GaAs applications increased remarkably (by a factor of 4.2) in the period 1971-1976. The applications identified as most extensively studied were lasers, microwave devices, devices for integrated optics, light emitting diodes, solar cells and others (including photocathodes, photodetectors, nuclear detectors, ultrasonic detectors, temperature sensors, magnetic field sensors, electron emitters, biomedical probes and infrared windows).

The numbers of publications per year devoted to the above applications are given in Fig. 3. It is seen that in 1971 microwave devices were the predominant application of GaAs and that the research activity on this application did not increase appreciably in the following five years. During that period, on the other hand, a striking increase in the research activity on optoelectronic devices took place indicating their potentially dominant role in future applications; the number of publications on these types of devices increased by about an order of magnitude.

Light emitting diodes represent the only device area where research activity has diminished in the last five years. Consistent with the discussions of the recent workshop, this decline is attributable to two factors: the material's demands associated with the fabrication of LED's are relatively small as compared with those of other devices; in addition, significant inroads into solid state displays are being made by liquid crystal technology

Summary

On the basis of our literature survey analysis and the discussions in the recent GaAs Workshop we conclude that interest in GaAs applications is growing rapidly. There is a demonstrated need for improvement of the quality of bulk GaAs single crystals. The presently available single crystals are to a large measure responsible for the prevailing low yield and erratic performance of GaAs devices. The most significant future applications of GaAs will most likely be in integrated optoelectronics (including lasers) and photovoltaic cells for solar energy conversion.

TABLE I

GaAs Publications

(Primary Source: Chemical Abstracts)

	1971	1972	1973	1974	1975	1976	1977	Total
Total Number of Publications	922	988	961	1107	1353	1357	1427	8115
Patents	74	94	106	93	144	153	136	800
Publications in English (excl. patents)	489	518	482	610	699	790	859	4447
Other Languages (excl. patents)	359	376	373	404	510	414	432	2868

Geographic distribution of GaAs research and development within the U.S.A.

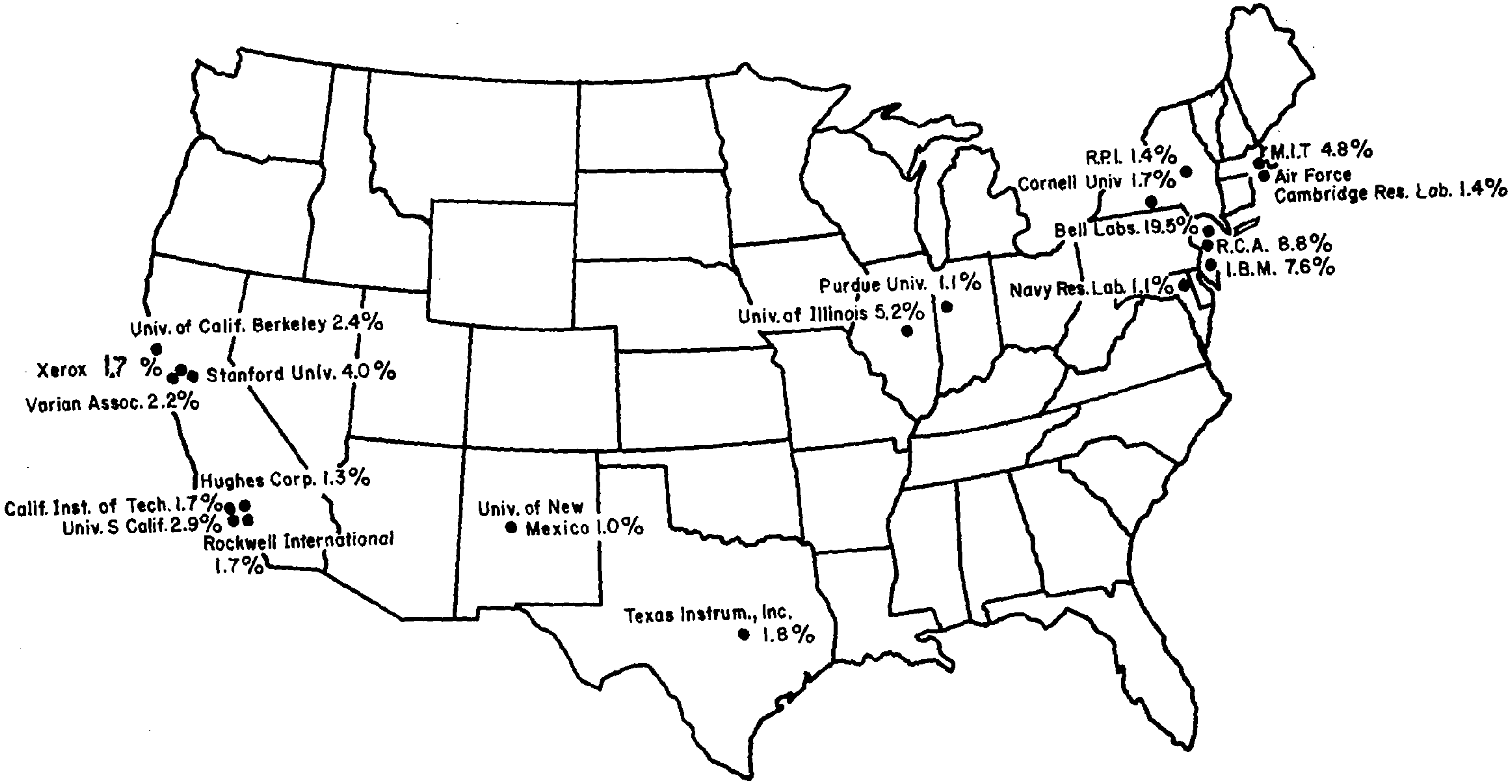

Figure 1

TABLE II

Publications in Open Literature on All Aspects of GaAs in the English Language

1971-1977

Organization	Percentage of Total Papers
Bell Telephone Laboratories	9.8
RCA	4.0
IBM	3.7
University of Illinois	2.6
M. I. T.	2.3
Hitachi, Ltd. (Japan)	2.3
Stanford University	2.0
Nippon Telegraph & Telephone (Japan)	1.7
Nippon Electric (Japan)	1.6
Karl Marx University (East Germany)	1.4
University of Southern California	1.4
Osaka University (Japan)	1.3
Electrotechnical Laboratory (Japan)	1.2
University of California, Berkeley	1.2
Philips (worldwide)	1.1
Standard Telecommunications Laboratories (England)	1.1
Varian Associates	1.1
University of Newcastle-upon-Tyne (England)	1.0
Fujitsu Laboratory (Japan)	1.0
Tokyo Institute of Technology (Japan)	.9
Max Planck Institute (West Germany)	.9
Texas Instruments	.9
Royal Radar Establishment (England)	.8
University of Tokyo (Japan)	.8
Institute of Semiconductor Physics (USSR)	.8
Rockwell International	.8
Xerox Corporation	.8
California Institute of Technology	.8
Cornell University	.8
Mullard Research Laboratory (England)	.8

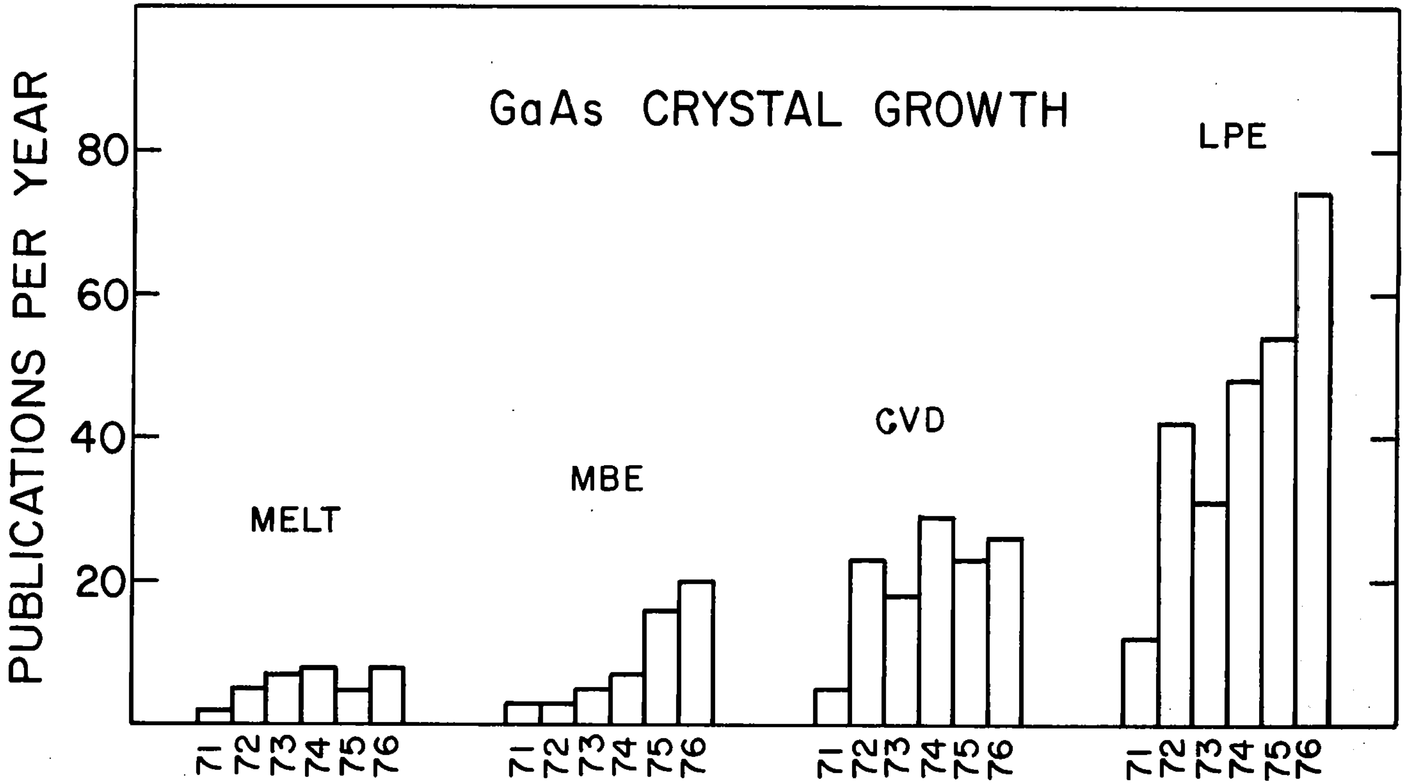

Figure 2 (MBE: molecular beam epitaxy; CVD: chemical vapor growth; LPE: liquid phase epitaxy)

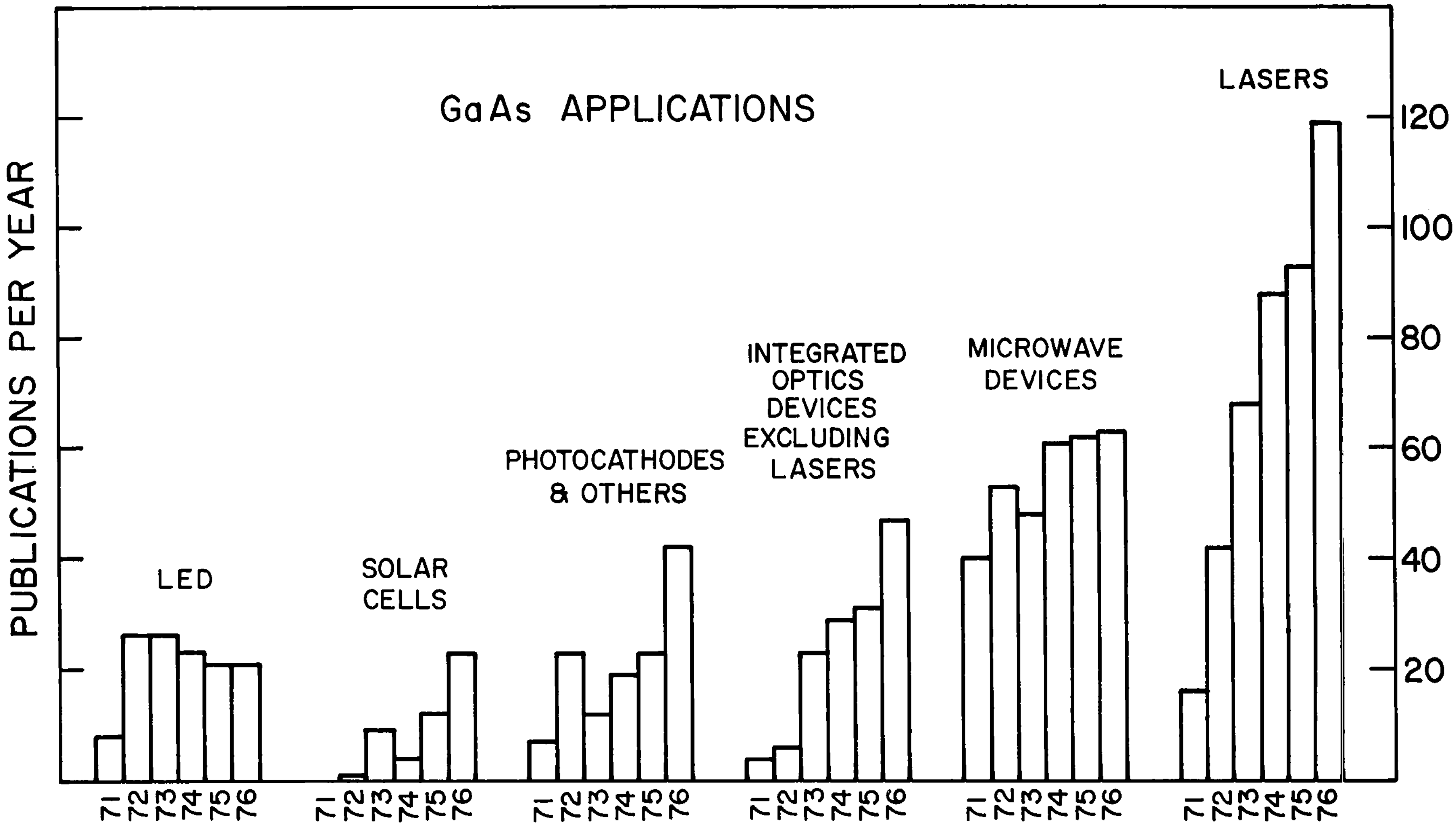

Figure 3: (LED: light emitting diodes)

PART B

WORKSHOP ON GaAs

Held November 14-15 and November 17-18, 1977
at the Colonial Hilton Inn, Wakefield, Massachusetts

Motivation and Objectives

Although our experience with materials processing in space has been relatively limited, two fundamental conclusions have emerged: (1) optimization of materials processing in space, i.e., exploitation of the unique advantages of zero gravity conditions is possible only if the problems associated with processing of the material on earth are clearly identified; (2) meaningful assessment of the role of zero gravity conditions in materials processing can be made only if reliable methods are available for the detailed characterization of the material before and after space processing.

Thus, in considering "Crystal Growth of Device Quality GaAs in Space", we felt that before the design of a successful growth process and before the ensuing benefits can be optimized we must first identify the unsolved problems associated with the growth of bulk GaAs in the presence of gravitational forces. We felt further that it is equally important to define the existing needs for reliable chemical, structural and electronic characterization methods which will permit to relate directly the salient materials parameters to the electronic characteristics of single crystal GaAs and in turn to device performance. Finally, we recognized that it is essential to assess the potential impact of high quality bulk GaAs crystals on solid state applications (devices and systems).

The workshop was conceived and organized with the above objectives in mind. It was scheduled in two two-day parts. The first was devoted to crystal growth and the second part to the characterization of GaAs and the role of its electronic characteristics in device applications and device performance. The format of the workshop was, by design, informal and flexible. No rigid program was planned but a general framework was formulated for guiding the discussions.

Experts from industry and universities participated (see attached list of attendees). Each general topic (see attached schedules) was introduced by a participant and was then pursued through informal discussions.

Although all discussions were recorded and, in the meantime, have been transcribed (several hundred typewritten pages), we have decided to attempt, at this time, to extract only the general comments and conclusions. They are presented here in a sequence which does not necessarily coincide with the sequence in which the general topics were discussed. At a later date we may attempt to summarize some of the specific discussions.

General Comments and Conclusions; Part A Crystal Growth

General Remarks

It was asserted that GaAs is established in the electronic device market and that its long-range role in solid state and optoelectronics should continue to be a definitive one. Although the GaAs device market is at present small compared with that of Si, the significance of the GaAs applications rests on the fact that they constitute a very important extension of Si device applications. Light emitting diodes, lasers and optoelectric devices represent some of the GaAs applications (often in conjunction with other III-V compounds). Other established applications of GaAs are in the field of microwave devices (Gunn diodes, MOS-FET) and charge couple devices. In addition, the feasibility of photovoltaic devices for solar energy conversion and of integrated optics based on GaAs has been demonstrated. In these types of applications Si or Si-systems still constitute an alternate solution. However, GaAs has distinct advantages over Si (direct and larger energy gap than Si) which in the long run may overcome its present shortcomings of high cost and availability in suitable quality and quantity.

Status of Bulk GaAs

GaAs device technology can be referred to as epitaxial technology (while Si devices are primarily based on diffusion technology) since it is indeed on epitaxial layers that active GaAs devices are fabricated. Bulk GaAs serves merely as a substrate to grow epitaxial layers. However, it was generally agreed that GaAs substrate is not a "passive" component in GaAs device structures.

The GaAs substrate has direct or indirect but profound effects, on the structural and electronic characteristics of the GaAs epilayers and devices. Diffusion of defects and/or impurities during the fabrication of devices, or while these devices are in service, is a major factor in the low yield, poor reproducibility and poor life encountered in GaAs device technology.

It was readily agreed that the quality of generally available GaAs crystals is very poor in terms of defects, electronic properties and stability. Although work on GaAs has been in progress for at least 25 years, still growth of GaAs single crystal remains an irreproducible or erratic art. What is even worse, various point defects and background impurities cannot, by and large, be identified individually, but rather they are referred to indirectly or are surmised through indirect macroscopic determination of electronic properties. Linear dislocations are perhaps the exception.

Again with the possible exception of linear dislocations, no reliable correlations exist between melt-growth parameters and the incorporation of a multitude of defects. Yet in this country no fundamental research on the growth of GaAs from the melt is known to be in progress in industrial or academic institutions.

Presently the major suppliers of GaAs crystal are two or three relatively small industrial organizations. The general consensus was that the feed-back between suppliers and users is rather poor so that the suppliers cannot be guided in their development work for improving systematically growth technology and the users are handicapped in developing an understanding of the origin of the encountered defects.

In view of the unavailability of bulk GaAs of sufficiently high quality the electronic industry seems to accept low yields and poor reproduciblity as a matter of fact. Actually, the high cost of fabricating GaAs devices--exceeding by more than an order of magnitude the cost of the substrate material--has led to the prevailing situation whereby only carefully selected GaAs wafers representing a small fraction of the supplied bulk material are being used. It was felt, however, that this situation is not satisfactory and that it will become a major problem as the demand for GaAs devices increases.

The need for drastic improvement in the quality of GaAs crystals is acutely recognized for those involved in device development and fabrication.

Reason for Present Status of GaAs

For the last twenty-five years the promising potential of GaAs device applications has hardly been questioned, and in fact GaAs always has been and still is considered to be the material of the future. Thus, the present low level of development of GaAs crystals appears incongruous.

A closer look makes it apparent that the research on bulk GaAs crystal growth over the years has not been on an ascending or even on a constant trend; rather, it has been on and off, and when on it never reached a broad-based effort.

It was recognized that the primary reason for the above research and development mode is the fact that no device or system with a substantial and sustainable market has been convincingly demonstrated or developed to justify large private investment in bulk GaAs growth.

For example, some early development effort on devices (to utilize the direct energy gap of GaAs and its high electron mobility) such as on avalanche diodes and high speed logic was stifled by the realization that advanced Si technology could perform more reliably and more profitably their functions, particularly since achieving the full potential of GaAs technology could only be seen in the distant future. This attitude, which was perhaps justified from the industrial sector's point of view, led to a real set-back of GaAs research and development.

The development of the light emitting diodes was the first product of some tangible market value; this development augmented by the applications of GaAs microwave devices, resulted in a renewed interest in GaAs single crystals. But even in this case the size of the market and the relatively low materials demands for fabricating light emitting diodes could not justify an upward trend in the magnitude of the research and development of GaAs crystal growth. This situation has been further aggravated by the inroads of liquid crystals in solid state displays.

The interest in lasers and optoelectronic devices for optical communications and optoelectronics is presently intense. However, the volume of such devices does not again justify on an economic basis development of GaAs single crystals, since the small amount of substrate material required can be selected, at least presently, from large volumes of available single crystals.

Significant markets for GaAs photovoltaic devices in large scale solar energy conversion can be seen in the distant future. However, the private industry does not appear to be ready for major forward moves in GaAs research and development.

It is very important to point out that in the process of analyzing the evolution of GaAs single crystal technology, no significant surprises were expressed as it was recognized that even the early Si single crystal development was not initiated by the private sector but rather received its impetus from government and particularly defense-oriented needs.

Thus, the inescapable conclusion emerged that advanced development of GaAs single crystal technology is unlikely to be undertaken by private industry in the foreseeable future and can be only brought about through substantial government support.

Assessment of Crystal Growth from the Melt

The annual world production of GaAs single crystals, estimated to exceed ten tons, relies on two primary methods, Czochralski growth (Liquid Encapsulation Czochralski) and horizontal boat growth. Both methods yield crystals of a size (approximately 1 1/2" in diameter) which is adequate for existing device processing needs.

In general, the GaAs single crystals obtained by both methods are inhomgeneous on a macro- and microscale, they have dislocation densities of 10^4 to $10^5/cm^2$, they contain significant amounts of point defects, background impurities and often Ga micro-precipitates.

It is generally agreed that LEC has a better reproducibility than boat growth, however boat growth yields occasionally good quality crystals.

Crystals free of lincear dislocations have been obtained by both methods, but they were found to be totally unsuited for device fabrication, probably due to their high concentration of point defects and of dislocation loops.

Residual Si and O impurities introduced through the quartz crucibles or ambient atmosphere constitute a major problem as they can reach concentrations as high as $10^{17}/cm^3$. The use of pyrolytic BN crucibles has yielded semi-isolating crystals of GaAs without intentional doping. Zone-floating is a very complex process in the case of GaAs and has not been investigated to any appreciable extent.

The most difficult problem in considering GaAs crystals is that of stoichiometry. Although it is generally agreed through indirect evidence that deviations from stoichiometry do occur, no direct practical method is available for the determination of such deviations. The problem is compounded by the fact that the Ga-As phase diagram near the stoichiometric GaAs composition is not accurately determined. It is agreed that deviations from stoichiometry are directly related to point defects and defect-complexes which are electronically very active and detrimental to device performance. Although the electronic levels introduced by point defects can be determined, the understanding of their origin, their kinetics and their physical interactions leaves indeed much to be desired.

No correlation between point defect formation and growth parameters are available. It could be assumed, however, that temperature fluctuations at the growth interface cause deviations from stoichiometry.

In summary, the major problems encountered in GaAs single crystals are inhomogeneities, point defects, defect-complexes, linear defects and residual impurities.

On very rare occasions and for entirely obscure reasons, a single crystal or a part of a single crystal of superior quality has become available on which devices of superior performance have been made. Rare as it may be, this fact indicates that the poor quality of GaAs crystals is not necessarily inherent to melt growth.

Epitaxial Growth

Expitaxial growth of GaAs (Liquid Phase Epitaxy and Chemical Vapor Deposition) has been far more extensively studied and is certainly better understood than melt-growth since device fabrication is exclusively based on epitaxial layers. Inherently, epitaxial growth is easier to control than melt-growth, and since it is carried out at lower temperatures than melt-growth contamination problems become much less severe. Indeed, very high quality epitaxial layers can now be readily prepared. However, a contributory factor to the development of epitaxial growth has been the poor quality of GaAs crystals. In fact, with the realization that epitaxial layers are not immune to the defects of the substrate, extensive efforts have been made (introduction of "buffer" layer between substrate and epitaxial layer, empirical heat-and chemical-treatments of the substrate) to minimize these effects. The results of these efforts have in some instances been successful and in others irreproducible and erratic. Epitaxial growth for the fabrication of devices is not a fool-proof escape from the inadequacy of the substrate material.

The question was discussed as to whether or not epitaxial methods (LPE of CVD) could be adapted for the growth of good quality bulk GaAs. The issue resolves into one of growth rates. It was the consensus that the present rates of epitaxial growth (10^{-2} to 10^{-3} cm/h) needs to be increased by about two orders of magnitude if a practical gain is to be realized. It was recognized that in an epitaxial configuration one of the limiting factors is associated with the dissipation of the latent heat of fusion. However, special heat sinks or Peltier cooling have not been given sufficient theoretical or experimental consideration. Kinetics limitations imposed by temperature well below the melting point were also considered, however, no specific recommendations became apparent.

In the case of LPE the growth rates could be increased by increasing the As concentration in the Ga solution (and thus increasing the growth temperature). Limited experience with growth from As-rich solution indicates that for As concentrations ranging from 25 to 75% the quality of GaAs is poor.

The issue of non-conventional approaches to the growth of improved bulk GaAs was raised. Although the need for such approaches was recognized, specific concepts did not emerge. The thought was put forth, however, that if epitaxial growth could be scaled up to encompass large areas, the drawback of small growth rates could be compensated to some extent, since the required thickness of substrates is of the order of one millimeter.

Closing Remarks

The general impression conveyed in this part of the workshop was that the uniqueness of GaAs as an electronic-device material is undisputed and that the present interest in GaAs is on a stable positive trend which can be projected well into the foreseeable future. There are no positive signs, however, of impending research and development effort at a level required to solve the problems relating to the quality of GaAs and to characterization methods.

It was generally agreed that the workshop conducted informally an on unrestricted discussions of specific and general problems (e.g., scientific, engineering, economic, policy-based, management-based and political) was very profitable. In fact, it was suggested that workshops of this type be held at two- to three-year intervals.

Part B Electronic Characterization of GaAs Single Crystals and GaAs Devices

General Remarks

It was generally agreed that the interest in GaAs is on an ascending trend due to its potential in optoelectronic devices and solar cells and its established position in microwave devices. It is widely believed that most types of GaAs applications will rely on epitaxial technology which yields material of far better quality and controlled characteristics than melt growth.

It is recognized that, in general, the poor quality (particularly in terms of structural defects) of available bulk GaAs single crystals used for substrate material leads to extremely low yields and erratic behavior of GaAs devices. To minimize the substrate quality problem the practice has been adopted whereby individual wafers are semi-empirically selected to be used as substrates. In many instances the wafers selected represent a very small fraction of the original single crystal and often entire single crystals are rejected. This practice is apparently considered by the industrial sector economically preferable to investing in melt-growth research and development and on the basic characterization of bulk GaAs. There are no positive signs of impending drastic changes of the present practice. Light emitting diodes are the only class of devices where the materials requirements are not severe and, thus, careful selection of wafers for substrates is not necessary.

In some types of devices such as FET's and heterostructure lasers a low dislocation density substrate was considered to play a secondary role. However, the effects of the substrate on these devices are not sufficiently understood so that one cannot differentiate with certainty the effects of device fabrication processes and those of the substrate method.

Characterization of Bulk GaAs

Although GaAs substrates are not as a rule carefully characterized, methods for the characterization of the electronic parameters of bulk GaAs on a macroscale are considered to be well developed. Thus, methods are available for the determination of carrier concentration, carrier mobility, minority carrier lifetime, compensation ratio, impurity levels, and surface characteristics.

Significant needs, however, were identified for the characterization of the electronic parameters on a microscale. Thus, in the cases where the substrate is an active part of the device, such as in single heterostructure lasers and solar cells, it is very important to determine on a microscale variations of carrier concentration and the distribution of energy levels. At present, electroreflectance and Schottky barrier probes can be used to some extent for carrier microprofiling. Scanning electron microscopy in the EBIC mode is very promising for obtaining three-dimensional profiles of the minority carrier lifetime and possibly of other electronic parameters. However, further research is necessary to understand the role of the excitation level and other processes associated with determination of electronic parameters by SEM.

Methods for the direct chemical structural characterization of bulk GaAs are not nearly as well developed as for the characterization of the electronic parameters. Modern methods for chemical characterization for surfaces such as ESCA, ion microprobe, and Auger spectroscopy are extremely useful and, in conjunction with etching or sputtering, can be extended to the chemical characterization of the bulk.

A major problem in the characterization of bulk GaAs is the identification of point defects (line defects can readily be identified by etching, x-ray diffraction and transmission electron microscopy techniques). It is recognized that vacancies, interstitial and substitutional point defects play a very critical role in the performance and service life of most GaAs devices, on concentration levels for which there are no direct identification methods available. Diffusion constants for point defects as high as $10^{-8} cm^2/sec$, at 700°C, have been reported, so that they can diffuse during epitaxial growth from the substrate to the epitaxial layer.

Point defects may form complexes such as vacancy-interstitial, vacancy-substitutional atom, etc. Understanding of the nature of such complexes is in its embryonic stage, again because no methods are available for their direct characterization.

It is agreed that point defects introduce recombination centers, and more importantly, nonradiative centers. There are indications (from electroluminescence experiments) that there are recombination centers accompanying dopant fluctuations in bulk GaAs crystals; these centers are attributed to point defects. It has been also found that nonradiative recombination on point defects releases sufficient energy to cause movement of the point defects even at room temperature. It is believed that interaction of migrating defects with dislocation loops and stacking faults can lead to the formation of recombination spots which contribute to the degradation of devices; the formation of "dark lines" in heterojunction lasers is one such example. Although diffusion due to nonradiative recombination is relatively slow, the desired life of heterojunction lasers is specified as 10^5 hours; during such long periods of time defect diffusion either within the epitaxial layer or from the substrate to the epitaxial layer (in single heterojunction lasers) can readily lead to device deterioration. These types of processes could be also detrimental in solar cells operating under high radiation intensity.

Another interesting but not completely understood aspect of point defects is the role of transition metal impurities. There are indications that such impurities, even at very low (residual) concentration levels in GaAs can increase significantly the lifetime of the minority carriers, apparently due to their interaction with other point defects. Experiments in which transition metal impurities were intentionally diffused in GaAs support this point of view. However, the direct identification of the type of defects involved and their direct correlation with the observed effects cannot be experimentally achieved.

At present, point defects can be characterized only indirectly through their electronic characteristics. Methods used for this purpose are cathodoluminescence, photoluminescence, transient deep level spectroscopy (based on differential capacitance techniques) and others. Although sufficiently developed, these methods are not considered simple or of a straightforward routine nature.

It was the feeling of the majority of the participants that deviation from stoichiometry is a key issue and a major problem in GaAs, as it is believed to be the primary cause of point defects. Yet there are no direct methods available for determining such deviations. Only calorimetric titration has been, reportedly, used successfully in GaP with a sensitivity of 10^{-5} (i.e., deviation from Ga/P = 1); this method is extremely difficult to use and its reliability has not as yet been verified. It was felt that in the absence of information on the absolute deviation from stoichiometry, even determinations of relative deviations would be of significant value. Indirect methods such as transient deep level spectroscopy--presently extensively studied--provide information on the electronic states of some deep traps which are believed to be due to point defects associated with deviations from stoichiometry.

Although theoretical models have been proposed, it was recognized that reliable experimental correlations between growth parameters and point defects are essentially non-existent; yet it is apparent that such correlations would elucidate the origin and incorporation mechanisms of point defects.

Device Characterization

Since device performance rests on interfaces, i.e., p-n homo- and heterostructures, it is considered that electronic, structural and chemical characterization of such interfaces is essential. Regarding characterization of electronic parameters, methods developed for the determination of surface electronic parameters are applicable to interfaces. In fact, methods based on capacitance, photovoltage and other optoelectric effects are used for determination of interface states and interface recombination velocities. Indirect methods such as electro- and photoluminescence are also very useful; it was pointed out that there is experimental evidence (through indirect methods) indicating that the interface recombination velocity in heterostructures (10^3 to 10^4 cm/sec) is two to three orders or magnitude smaller than that of GaAs surfaces. It was felt that only a limited amount of work is being carried out in this area.

Regarding GaAs-metal interfaces it was pointed out that much remains to be done and understood. In this context results on II-VI compounds were discussed which indicate that the interaction of anion and the contacting metal controls the interface characteristics (e.g., surface barrier) rather than the intrinsic semiconductor surface states.

With respect to chemical and structural characterization of interfaces, no reliable direct methods are available (as was pointed out in the case of bulk GaAs characterization) although acute needs for such characterization were identified.

Thus, it was pointed out that molecular beam epitaxy is successfully used for the fabrication of many non-active devices (such as 3-dimensional waveguides) and for majority carrier microwave devices. However, this method fails to produce consistently good GaAs/$Al_xGa_{1-x}As$ active structures. The reasons are not well understood; detailed characterization of interfaces resulting from MBE could prove extremely useful, as MBE appears to be the most promising method for achieving real integration (on a single chip) of active and passive devices.

Recent results indicate that in heterostructures the lattice mismatch can be largely (up to 70%) accommodated by elastic strain which in turn leads to changes in the energy gap, manifested as shifts in electroluminescence spectra. This phenomenon is not sufficiently characterized and studied.

Passivation of GaAs devices was recognized as a very important issue bearing on GaAs present and future applications. The present knowledge of oxide formation on III-V compounds and the properties of the resulting interfaces is not at a satisfactory level. For example, passivation of the laser mirror surfaces (to prevent deterioration from corrosion) is sufficiently developed but not adequately understood. Beyond the importance of passivation, it was pointed out that control of GaAs-oxide systems has far-reaching implications if one considers the vast spectrum of Si applications based on the control of the silicon-silicon oxide characteristics. Understanding of the GaAs oxide interface needs to be advanced far beyond its present level.

Closing Remarks

The general impression was sharply conveyed that GaAs technology is conspicuously lagging demonstrated or potentially feasible GaAs devices and systems. It became apparent that the necessary work on critical interfaces such as growth-characterization-device fabrication-device characterization-device performance is not being carried out at the required level. Significant potential applications in integrated optoelectronics and solar cells are clearly recognized. No optimism was, however, expressed for near future striking developments at the present level of research and development effort. At the same time no optimistic prognosis could be formulated regarding radical changes in effort within the industrial sector. The expectations, however, for the long-range GaAs applications remain high.

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Part A

Crystal Growth

November 14 and 15, 1977

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Part B

Electronic Characterization of GaAs Single Crystal and GaAs Devices

November 17 and 18, 1977

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16. Abstract

Part A

An extensive Literature Survey on GaAs was carried out for the period December 31, 1970, to December 31, 1977. The increasing interest in GaAs device structures increased steadily during that period. The leading research and development centers and the specific areas of interest were identified.

Part B

A Workshop on GaAs was held in November 1977 to assess the present status of melt-grown GaAs and the existing needs for reliable chemical, structural and electronic characterization methods. It was concluded that the present available bulk GaAs crystals are of poor quality and that GaAs technology is lagging demonstrated or potentially feasible GaAs devices and systems.

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